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ORIGINAL PAPER

Anomalously heavy monthly and seasonal precipitation in the Polish Carpathian Mountains and their foreland during the years 1881–2010

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Abstract The paper addresses the frequency, amount and geographic coverage of anomalously heavy precipitation in southern Poland in relation to atmospheric circulation at the monthly and seasonal scales between 1881 and 2010. The Carpathian Mountains and their foreland were selected for the study as an area known for its high precipitation totals and frequent precipitation-triggered natural disasters, such as floods and landslides. Records from 18 stations were used to identify anomalously heavy precipitation (AHP) defined for the purposes of the study, as the top quartile ($Q_{75\ \%}$) plus 1.5 times the interquartile gap (H) of the precipitation total ($P \geq Q_{75\ \%} + 1.5H$). The study found that most cases of AHP were recorded at one single station each. This suggests that, in addition, to the influence of circulation, local factors also play a major role in the formation of particularly heavy precipitation. The greatest absolute anomalously high precipitation totals were recorded in two disparate parts of the study area: (i) its western part exposed to wet air masses from over the Atlantic Ocean brought in by the dominant western circulation in the temperate zone and (ii) elevated parts of its south-eastern part. Two months with AHP (AHP months) occurred over the entire area (18 stations) in May 1940 and 2010. The latter case had both the greatest absolute totals (over 500 mm) and relative totals defined as their ratio to the long-term average (500 %), and it triggered a catastrophic flood in the Upper Vistula basin.

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1 Introduction

Periodic surpluses or deficits of precipitation may be regarded as dangerous meteorological and hydrological events. If sufficiently large, they can have a significant impact on numerous areas of human activity. Over long spells, they lead to excessive water surpluses or acute droughts. The temperate European climate, mainly influenced by the strong variability of atmospheric circulation, is characterised by the occurrence of long spells of various types of weather, including heavy precipitation, heat waves and cold periods (Twardosz and Kossowska-Cezak 2015). Some studies also suggest a potential role of increased concentrations of carbon dioxide in an increased incidence of extreme precipitation (Palmer and Räisänen 2002; Räisänen 2005). Räisänen (2005) uses ensemble averages to claim that the variability increases slightly in most areas, so that the contrast between the high and low precipitation extremes grows larger with increasing CO_2.

The objective of the study was to determine the quantity, frequency, duration and spatial extent of anomalously heavy monthly and seasonal precipitation and the type of circulation favouring the formation of such precipitation in the Polish Carpathian Mountains and their foreland between 1881 and 2010. The project was inspired by the exceptionally wet May of 2010 that caused catastrophic floods and numerous landslides in much of Central Europe (Maciejowski et al. 2011;

Woźniak 2012, 2013). Christensen and Christensen (2003) suggest that, in future, catastrophic floods of this type are likely to increase in frequency in this part of the continent. Areas prone to exceptionally high rainfall totals, whether daily or monthly, include, in particular, mountains where the effect is augmented by adiabatic cooling of moist air masses in forced ascent. For this reason, the highest precipitation totals, regardless of the time interval, are recorded in mountainous areas of low and medium latitudes, including Poland (for example, the daily total of 300 mm in Hala Gąsienicowa in the Polish Tatra Mountains on 30 June 1973).

Existing studies on precipitation in different areas of southern Poland found no clear-cut trends in the totals (Niedźwiedź et al. 2009; Woźniak 2013). The latest IPCC Report (IPCC 2013), on the other hand, states that the frequency and intensity of heavy precipitation events have likely increased in Europe. In particular, it finds an increase in the frequency of months with anomalously heavy precipitation (Schönwiese et al. 2003; Benestad 2005). Moreover Schönwiese et al. (2003) demonstrated that the increase of extreme wet months is reflected in both a systematic increase in the variance and in the Weibull probability density function parameters. Trömel and Schönwiese (2007) showed that tendencies in the probability of occurrence for extreme values of observational monthly precipitation time series in Germany depend on the season and also vary from region to region.

2 Sources and data

The study is based on monthly totals of precipitation recorded at 18 stations, including 14 in the Polish Carpathian Mountains and 4 in their foreland (Table 1, Fig. 1), during the period 1881–2010. The stations were selected to represent low-altitude Carpathian catchment basins.

The monthly precipitation database was built using numerous publications of the Polish weather service, especially its annual hydrographical, meteorological and precipitation reports. The oldest precipitation data, 1881–1890, were found in the study of Hellmann (1906). The period 1895–1912 was completed with data from the Austro-Hungarian *Jahrbuch Hydrographischen Zentralbureaus k. k. Ministeriumfűrőffentliche Arbeiten*. Data after 1982 was found in other available Polish sources (Poland's Main Statistical Office) and on the web service of the *European Climate Assessment & Dataset* (ECA&D) www.eca.knmi.nl. To account for the relocation of some of the stations over the 130-year period, the records were verified for homogeneity. Alexandersson's *standard normalised homogeneity test* (SNHT) was used to test the hypothesis that the monthly totals were homogenous (Alexandersson 1986). Other series of records were tested using the homogenous series from Krakow. In the light of the results, it was concluded that, at the level of significance of 0.05, there

Table 1 Details of the weather station locations (arranged from west to east)

Station		Altitude (m a.s.l.)	Geographical coordinates (°, ′)		Average totals (mm) ± standard errors
No	Name		φ N	λ E	
1	Wisła	433	49 39	18 51	1187 ± 16
2	Bielsko-Biała	322	49 48	19 00	994 ± 15
3	Żywiec	354	49 41	19 12	879 ± 14
4	Wadowice	268	49 52	19 30	748 ± 11
5	Maków Podh.	359	49 43	19 41	908 ± 14
6	Kraków	206	50 03	19 57	681 ± 10
7	Myślenice	290	49 49	19 57	872 ± 14
8	Rabka	510	49 37	19 58	882 ± 11
9	Zakopane	844	49 17	19 57	1131 ± 16
10	Nowy Sącz	292	49 37	20 41	728 ± 11
11	Krynica	613	49 24	20 57	861 ± 13
12	Tarnów	225	50 01	20 59	706 ± 12
13	Jasło	240	49 44	21 28	720 ± 12
14	Dukla	351	49 34	21 40	833 ± 13
15	Rzeszów	214	50 06	22 01	652 ± 11
16	Sanok	314	49 35	22 11	786 ± 13
17	Wetlina	700	49 08	22 28	1075 ± 18
18	Jarosław	204	50 01	22 41	697 ± 12

Fig. 1 Location of meteorological stations

were no grounds to reject the hypothesis of homogeneity of the monthly and annual precipitation totals.

None of the monthly precipitation series displays statistical trends of change over the 130-year study period. In this way, they meet the condition of being stationary.

A range of criteria used by climatologists to determine precipitation anomalies, especially the older ones, has been reviewed in numerous climatological studies and reports. One of the more popular methods used to identify anomalous months, seasons and years is the standard deviation, which, in most cases, is applied as a doubled or even tripled value (e.g., Schönwiese et al. 2003). In recent years, a percentile-based method has found its way into studies on daily (e.g., Łupikasza 2010) and monthly precipitation (e.g., Miętus et al. 2005). However, despite the method's growing popularity and even certain deliberate efforts to increase this effect, the fact that the frequency of anomalous values (determined from empirical distribution) in this method is itself a fixed value has ruled it out from a study that is trying to identify such frequencies. Another drawback, from the point of view of this study, is that the method does not utilise the concept of an anomaly as a deviation of a given value from at least a 30-year average, as defined by the WMO's International Meteorological Dictionary (International Meteorological 1992).

In their selection of a cut-off criterion, the authors adopted a slightly different approach. Since anomalies, by definition, are rare, the anomalously high totals were identified to fit between the top quartile ($Q_{75\ \%}$) plus 1.5× the interquartile gap H ($H = Q_{75\ \%} – Q_{25\ \%}$) and the highest value of the record. In statistics, values exceeding the interquartile gap are known as "extreme" and those exceeding triple the value of the gap are known as "outliers" (Statistica 2010). Such outlier values may be regarded as either errors of measurement or errors in recording, or, alternatively, as a result of exceptional conditions that caused such values to actually occur (Stedinger et al. 1993). In the case of precipitation, which is characterised by high natural variability of timing, values exceeding the upper quartile plus 1.5× the interquartile gap will be regarded as non-standard values that deviate considerably from the typical statistical distribution, in other words: anomalous values.

The "interquartile" criterion is defined by the formula:

$$1.5*(q(0.75) - q(0.25)) + q(0.75)$$

where $q(p)$ means p-quantile. The factor 1.5 is chosen on the basis of experience in precipitation data analysis as a figure giving extreme precipitation similar to that defined by intuition. The criterion would obviously be profoundly dependent on the shape of the right-hand tail of the probability distribution which describes the data. Since possible theoretical models are different and, moreover, may be modified by assuming different values of the shape parameter, the interquartile criterion would be equivalent to quantiles in the range from 0.9 to 0.997 (Fig. 2). The first value was obtained with a Pareto distribution with a shape parameter $c = 2$ and the last with a normal distribution. The interquartile criterion itself does not assume any particular model, as it is based on empirical quartiles.

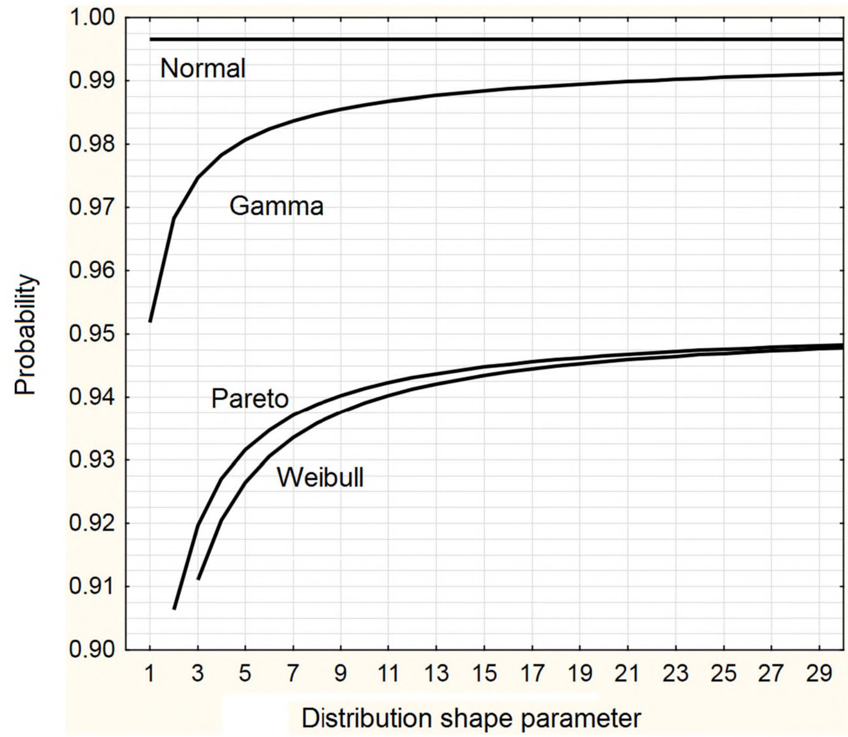

Fig. 2 Equivalence of the interquartile criterion to probability (i.e. quantile) according to four distributions. The probability depends on the shape parameter of the given distribution (excluding normal, which has no such parameter). The highest $p = 0.9965$ is obtained for normal distribution, and the lowest asymptotic $p = 0.951$ produces the Pareto as well as the Weibull distributions

The interquartile criterion was selected for its superior precision in obtaining of the final result when compared to a simpler choice of quantiles Q95 or Q99. Since Q95 and especially Q99 are based on an inherently limited observation samples, the relative errors of their values are large. In contrast, quantiles Q25 and Q75 are free from this deficiency. In a sample of $N = 300$, the expected errors of quantiles (calculated according to the binomial distribution) are as follows: Q75—10 %, Q95—25 % and Q99—57 %.

In summary, the proposed method of identifying anomalously heavy precipitation has been clearly defined and is simple to use. The number of months with anomalously heavy precipitation matches intuitive expectations, i.e. a range from no such cases (0) to a maximum of nine, which is discussed later on.

This study focused chiefly on months with anomalously heavy precipitation and seasons, but some consideration was also given to years with anomalously heavy precipitation.

In order to identify a dependence of anomalously high monthly precipitation on atmospheric circulation, the authors used the calendar of circulation types in southern Poland devised by T. Niedźwiedź (1981, 2014).

3 General description of the precipitation

During the study period, the study area received, on average, between ca. 650 mm of precipitation in the Carpathian foreland (Rzeszów) and nearly 1200 mm in the Beskid Śląski Mountains (Wisła) in the westernmost part of the area exposed to wet westerly winds (Table 1). In particular, the highest precipitation totals of the period, at ca. 1700 mm, were recorded in the highest Carpathian range of the Tatras, but stations from this range were not included in the study, as their earliest complete series of records was only in the mid-twentieth century. Precipitation generally increased not just with an increase in altitude along the N-S axis, but also with longitude from east to west (i.e. with a decreasing continental component of the climate). Landform also played a role, as precipitation totals were significantly lower in mid-mountain basins, e.g. Nowy Sącz (Table 1).

There is one general annual precipitation pattern across the area: the values peak in July and bottom out in February or January. This is illustrated by three stations: Kraków, Rabka and Zakopane, representing the N-S altitude profile (Fig. 3). The totals in summer are approximately three times greater than in winter. The average precipitation gradient is 60 mm per 100 m of altitude (Niedźwiedź and Obrębska-Starklowa 1991), but the actual values are strongly dependent on the exposure of the slopes and the vertical climate zone.

4 Frequency of months and seasons with anomalously heavy precipitation and seasons

During the study period, there were 712 cases of monthly anomalously heavy precipitation (AHP), i.e. 2.5 % of all station-months in the period (12 months × 18 stations ×

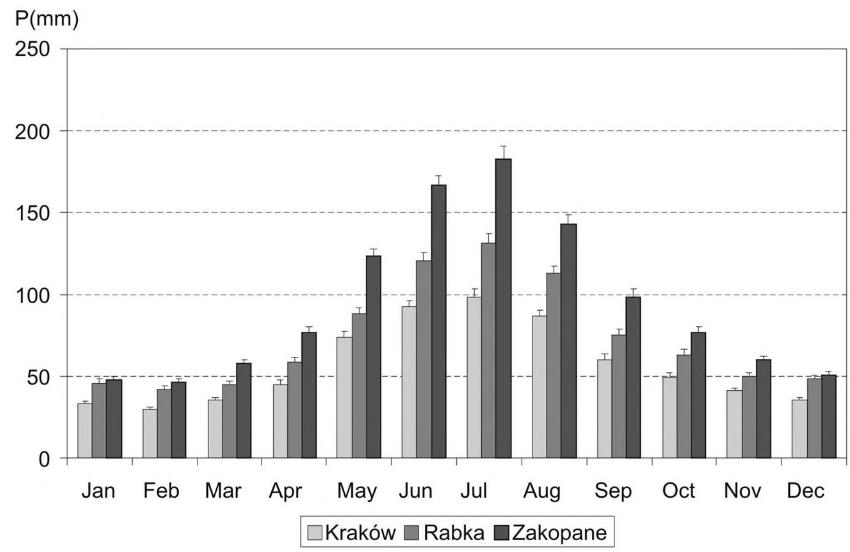

Fig. 3 Annual variation of precipitation at selected stations (mm) and their standard errors

130 years) (Table 2). This translates into nearly 40 months (39.6) with AHP, on average, at each station, which means that, in a given calendar month, there were, on average, 3.3 months with AHP with AHP in a given calendar month per ca. 40 years. The number of AHP months per station varied widely from 29 in Rzeszów to 48 in Nowy Sącz (Fig. 4).

The annual count of AHP months varies widely. Of the 712 AHP months identified (Table 2), the highest numbers were found in May and July at 86 each (i.e. 24 %) followed by February at 80 (i.e. 11 %); the lowest was recorded in November at 32 (i.e. 4 %). To put the seemingly high overall number of AHP months of 712 in the right proportions as an anomaly, one should view it from the point of view of an individual station, which, on average, has to wait 3–5 years to record another AHP month. Certain stations recorded five calendar months without any anomalously high precipitation total. On the other hand, the highest incidence of AHP months at a single station was 9 (July in Jasło).

The 712 AHP months occurred in 212 months (13.6 % of months), which means that there were years when an AHP month was recorded at more than one station in a single calendar month. May was the no. 1 month of this type with AHP months recorded in 15 years of the period at 18 stations (Table 2). This means that, on average, six stations recorded AHP in the same May. At the other end of the spectrum, the smallest number of stations recording anomalously heavy monthly precipitation was 2 in November (32 AHP months in 15 years, Table 2).

The study also investigated seasons with (AHP seasons) and found 173 such occurrences (Table 3). This gives an average of nearly 10 (9.6) AHP seasons per station or 2.4 AHP seasons per calendar season, i.e. one seasonal AHP per approximately 50 years. The actual distribution varied broadly from 2 at Jarosław to 50 in Bielsko-Biała, Maków Podhalański and Dukla. The most represented season was autumn at 68 (i.e. 39 %), and the least represented was winter at just 21 (i.e. 12 %) (Table 3). In other words, during the study period, the average number of AHP seasons varied from ca. 1 in winter to ca. 4 in autumn. All stations recorded a seasonal AHP in autumn, one station had no springtime AHP season, and five stations noted no such seasons in summer and winter. When the overall number of AHP seasons and the number of years with an AHP season are compared, it transpires that the same spring or autumn with AHP was recorded at three to four stations (Table 3), while summers and winters with AHP were smaller in area at just two stations on average.

The study also identified 27 years with AHP (Table 3). Five stations recorded three such years, while Wisła and Zakopane recorded none. All such years were recorded by just one station in a given calendar year producing an average of 1-year AHP per station (27 AHP years in 27 years, Fig. 4).

5 Anomalously high totals

Anomalously high precipitation totals varied very widely across the study area. In all three intervals studied, i.e. months,

Table 2 The number of cases (1.) of AHP months and the number of months with AHP (2.) (1881–2010)

	Jan	Feb	March	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Jan–Dec
1.	52	80	44	56	86	67	86	60	66	43	32	40	712
2.	16	21	15	20	15	24	19	20	19	13	15	17	212

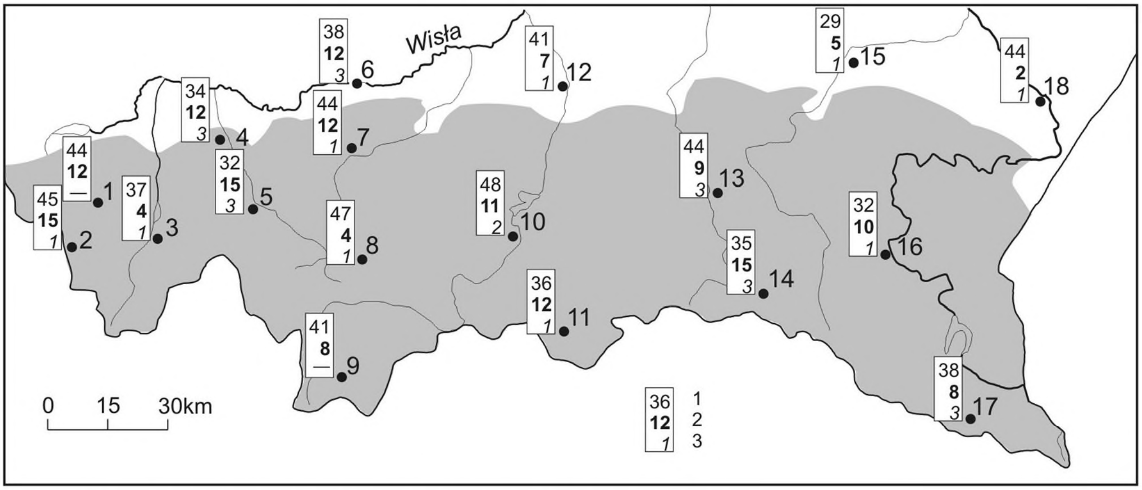

Fig. 4 Number of AHP months (*1*), AHP seasons (*2*) and AHP years (*3*) at particular stations

seasons and years, the highest AHP values were more than twice as high as the lowest AHP (Tables 4 and 5). There was a general spatial pattern where the lowest AHP totals were recorded in the Carpathian foreland and in mid-mountain basins (Nowy Sącz), while the highest values were observed in the westernmost Beskid Śląski range (Wisła) and in the south-eastern Bieszczady range (Wetlina).

The lowest levels of the anomaly were recorded between November and March, while the highest values fell between April and September, which is explained by the annual precipitation cycle. The values ranged from 44.5 mm in December in Tarnów (1959; P_{max} = 82 mm and $P_{av.}$ = 37 mm) to 425 mm in May in Wisła (2010; P_{max} = 536 mm, $P_{av.}$ = 111 mm) (Table 4).

In relative terms, i.e. the AHP percentage of the average monthly precipitation, the size of the anomaly ranges from an AHP_{max} of 245 % in January 1976 in Wadowice to 484 % in May 2010 in Wisła (Table 4). The greatest relative anomaly, however, was not an AHP_{max}, but an AHP in May 2010 at Żywiec at 500 % of the average, when the total was 463 mm ($P_{av.}$ = 93 mm). This means that the greatest anomaly can exceed the lowest anomaly by more than a factor of 2.

A comparison of extreme seasonal AHP values reveals that the highest wintertime AHP is lower than the lowest summertime AHP (Table 5).

Table 6 summarises the 10 months with the highest totals in absolute (mm) and relative (% of average) terms. Over the 130-year period, 10 months is equivalent to a frequency of ca. 5 %. July (6) was the most frequent month in this summary and came up mostly in the west of the area where the exposure to the wet westerly winds is the greatest. No such clear-cut pattern was found among the highest relative values, as they occurred in different months and locations.

Among seasonal precipitation totals, the highest values were recorded in summer at western stations and in the highest located stations in the south-eastern part (Table 7). The greatest surplus values over the long-term averages were recorded in all seasons. The maximum reached three times the average (spring of 2010 in Wadowice).

The greatest surplus of years with AHP over the long-term average (177 %) was recorded in 2010 in Krakow and the lowest (144 %) in the same year at Dukla.

Table 3 The number of cases (1.) of AHP seasons and AHP years and the number of seasons and years with AHP (2.) (1881–2010)

	Winter	Spring	Summer	Autumn	Σ	Year
1.	21	51	33	68	173	27
2.	13	15	17	19	64	27

6 Spatial extent of monthly and seasonal AHP

Out of the 212 AHP months, 43 % (91) occurred at a single station and 18 % (39) at two stations, which were not always neighbouring stations and were sometimes located very far apart (Table 8). In total, nearly 71 % of AHP months (151) were recorded at three or fewer stations. The calendar of AHP months contains all 38 such occurrences recorded at six or more stations (one third of the total stations) (Table 9).

An AHP month was recorded simultaneously at all 18 stations on only two occasions: in May 1940 and May 2010. The latter case involved the highest totals ranging from 179 mm (263 % of the average) in Rzeszów to 536 mm (484 %) at Wisła, and 11 of the stations, mostly located in the western part of the area, recorded their maximum totals in the 130-year period. This record spell of precipitation triggered a flood in southern Poland (Maciejowski et al. 2011). This catastrophic flood claimed more than ten lives and caused unprecedented levels of damage to infrastructure. It also contributed to the activation of numerous landslides, which destroyed hundreds

Table 4 Extreme values of AHP months and their characteristics

Months	AHP_{min}				AHP_{max}			
	P (mm)	Year[a]	%[b]	Station	P (mm)	Year[a]	%[b]	Station
Jan	85	1976	245	Wadowice	168	1976	326	Krynica
							244	Wisła
Feb	89	1977	271	Tarnów	191	1946	303	Wisła
March	95	1887	254	Nowy Sącz	226	2000	298	Wisła
Apr	128	2001	242	Wadowice	233	1998	320	Wetlina
May	202	1940	296	Rzeszów	536	2010	484	Wisła
Jun	208	1884	238	Rzeszów	478	1884	321	Wisła
July	241	1913	259	Rzeszów	521	2001	377	Maków Podh.
Aug	188	1882	228	Tarnów	402	1925	294	Wisła
Sep	162	1904	288	Rzeszów	359	1996	354	Wisła
Oct	155	1936	332	Nowy Sącz	396	1974	419	Wetlina
Nov	98	1962	261	Nowy Sącz	270	1910	329	Wetlina
Dec	82	1959	219	Tarnów	210	1952	409	Bielsko-Biała

[a] Year of occurrence

[b] Percentage of average totals

of buildings, including residential. The former of the two AHP months, May 1940, only resulted in a record monthly precipitation in Rzeszów (202 mm or 296 %) and Jarosław (206 mm or 292 %). Some stations in the western part recorded higher absolute values (e.g. 281 mm in Bielsko-Biała), but in relative terms, they were not as extreme. Also, the monthly figures of May 1940 at most of the stations, especially in the western part, were about a half of those recorded in 2010. Nevertheless, the rainfall triggered floods along the entire upper Vistula valley, albeit with less significant effects than those in 2010. Just the year before, in 1939, another May AHP months were recorded at 15 stations when the highest absolute total was observed in Zakopane at 255 mm and the highest percentage anomaly in Wisła at 223 %. Again, this rainfall caused a flood, but of just local extent that mainly affected areas around Krakow.

There was one more AHP month in the warm half of the year that covered nearly all of the area. In total, 17 stations recorded AHP in September 2007 (Rzeszów was the only exception), while seven stations (Żywiec, Wadowice, Krakow, Myslenice, Rabka, Tarnów and Wetlina) noted their maximum rainfall totals of the study period. Additionally, the totals at Żywiec and Wisła (226 mm and 293 mm) represented the highest surplus of the average value at 290 %.

Two wintertime AHP months, in January 1976 and February 1946, also covered most of the study area. During the former, which covered 16 stations (except Bielsko-Biała and Sanok), 11 stations recorded their study period maximums. Wisła had the highest total, at 168 mm (244 %), and Żywiec recorded the greatest surplus, at 351 % (147 mm). The other AHP months included 15 stations (omitting Nowy Sącz, Krynica and Wetlina), of which five had extremely high totals, including again Wisła with the highest (191 mm) and Żywiec with the greatest surplus (314 %, 121 mm).

The AHP of June 1884 occurred at 13 stations, excluding those in a central-western section and the town of Jarosław. The maximum monthly total was recorded at Wisła, at

Table 5 Extreme values of AHP seasons and AHP years

Seasons and year	AHP_{min}				AHP_{max}			
	P (mm)	Year[a]	(%)[b]	Station	*P* (mm)	Year[a]	(%)[b]	Station
Spring	268	1897	174	Kraków	662	2010	247	Wisła
Summer	486	2010	175	Kraków	813	1925	182	Wisła
Autumn	275	1936	187	Nowy Sącz	620	1992	223	Wetlina
Winter	193	1976/77	183	Wadowice	395	1922/23	193	Wisła
Year	995	1966	156	Kraków	1709	1998	159	Wetlina

[a] Year of occurrence

[b] Percentage of average totals

Table 6 Months with the heaviest precipitation (1881–2010) (A—by precipitation total (mm) and B—by the amount by which it exceeds the long-term average (%))

A					B				
Lp.	mm	(%)[a]	Month and year	Station	Lp.	(%)[a]	mm	Month and year	Station
1	535	484	May 2010	Wisła	1	499	463	May 2010	Żywiec
2	521	377	Jul 2001	Maków Podh.	2	486	516	May 2010	Bielsko-Biała
3	516	486	May 2010	Bielsko-Biała	3	484	535	May 2010	Wisła
4	482	299	Jul 1997	Wisła	4	482	418	May 2010	Wadowice
5	478	321	Jun 1884	Wisła	5	419	396	Oct 1974	Wetlina
6	463	499	May 2010	Żywiec	6	409	210	Dec 1952	Bielsko-Biała
7	439	240	Jul 2001	Zakopane	7	402	154	Mar 1946	Jarosław
8	438	239	Jul 1960	Zakopane	8	399	157	Jan 1954	Sanok
9	437	271	Jul 1960	Wisła	9	398	140	Jan 1911	Nowy Sącz
10	433	269	Jul 1908	Wisła	10	393	251	Oct 1939	Maków Podh.

[a] Percentage of average totals

478 mm, and also represented the greatest relative anomaly of 321 %. Three other AHP months, in February 1977 and April 1898 and 1916, had a similar spatial coverage with 12, 13 and 13 stations, respectively. In the two April cases, five or six stations recorded their maximum precipitation totals of the study period. Also, the absolute and relative scales of the anomalies were similar with totals around 200 mm and surpluses of 380 %.

Another noteworthy groups of anomalies were ones recorded at a smaller number of stations, but where most of the stations noted their period maxima. These included October 1974, when six out of eight stations recorded maximum totals and July 2001 with six out of seven following the same pattern.

Certain months with AHP occurred in the form of small, but concentrated clusters of stations. Six such AHP months covered the western part (February 1952, March 1906 and 2000, July 1960, August 1882 and 1985), one the central part (September 1899) and two the eastern part of the study region (June 1948 and July 1980).

There is an interesting summertime pattern of AHP months with at least six stations (Fig. 5). The largest number of June AHP months occurred in the south-eastern part (including three in Sanok and at Wetlina), while only two occurred in the western part. In August, on the other hand, the western part had several AHP months, while the eastern had none.

The highest number of July AHP months occurred in the western and central-northern part, while, in the south-eastern and eastern parts, there were only one or two.

Roughly, a half of all seasons with AHP and years only occurred at a single station (Table 10) (respectively, 28 out of 64 AHP seasons, i.e. 44 %, and 6 out of 11 AHP years, i.e. 55 %), and nearly three quarters of AHP seasons (46, i.e. 72 %) occurred at three stations or less. There were four

Table 7 Months with the AHP (1881–2010) (A—by precipitation total (mm) and B—by the amount by which it exceeds the long-term average (%))

A						B					
Lp.	mm	(%)[a]	Seasons	Year	Station	Lp.	(%)[a]	mm	Seasons	Year	Station
1	813	182	Summer	1925	Wisła	1	278	495	Spring	2010	Wadowice
2	801	197	Summer	1968	Bielsko-Biała	2	277	550	Spring	2010	Żywiec
3	778	192	Summer	1960	Bielsko-Biała	3	269	617	Spring	2010	Bielsko-Biała
4	775	201	Summer	1913	Wetlina	4	260	377	Winter	(1910/11)	Zakopane
5	749	200	Summer	2001	Maków Podh.	5	259	397	Autumn	1992	Jarosław
6	714	224	Summer	1893	Sanok	6	247	474	Autumn	1931	Maków Podh.
7	714	245	Summer	1893	Jasło	7	247	662	Spring	2010	Wisła
8	712	185	Summer	1906	Wetlina	8	245	714	Summer	1893	Jasło
9	708	189	Summer	1934	Maków Podh.	9	239	694	Summer	1913	Jasło
10	694	239	Summer	1913	Jasło	10	239	519	Autumn	1930	Bielsko-Biała

[a] Percentage of average totals

Table 8 Number of AHP months (2) recorded at the same time in station number ranges (1)

	Number of stations																		
1.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Σ
2.	91	39	20	7	15	8	6	5	4	2	3	1	3	–	2	1	1	2	212

AHP seasons that covered six or more stations, i.e. the springs of 2010 (12 stations) and 1919 (6) and autumns of 1931 and 2007 (11 each). The single such annual period was 2010 with ten stations (Table 10).

Table 9 Calendar of AHP months recorded at least six stations

Year	Months	No of station	Stations (numbers as in Table 1)
1882	Aug	6	3, 6, 7, *9*, 10, *12*
1884	Jun	13	*1*, 2, *3*, *7*, *8*, *9*, *10*, *11*, 13, *14*, *15*, 16, 17
1894	Jun	6	1, 3, 8, *16*, 17, 18
1898	Apr	13	3, 5, 6, 7, *8*, *9*, *10*, *11*, 12, *13*, *14*, 16, *18*
1899	Sep	6	6, 8, 9, 10, 11, 12
1906	Mar	6	3, 4, 5, 6, 8, 9
1908	Jul	6	1, 2, 5, 6, 12, 13
1913	Aug	6	2, 10, *11*, *13*, *14*, *17*
1916	Apr	13	1, *3*, *5*, *6*, *7*, 8, 9, *12*, 13, 14, *15*, 16, 18
1919	May	6	2, 6, 7, 10, 13, 14
1931	Sep	11	1, *2*, 3, *5*, 7, 8, *9*, 10, *11*, 12, 14
1934	Jul	7	5, 7, *8*, 9, 10, *12*, *13*
1939	May	15	1, 2, 3, 4, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18
1939	Oct	11	2, *3*, *4*, *5*, *8*, 12, 13, 15, 16, 17, 18
1940	May	18	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, *15*, 16, 17, *18*
1946	Feb	15	*1*, 2, *3*, 4, 5, 6, 7, *8*, 9, 12, 13, 14, 15, *16*, *18*
1947	Nov	9	1, *2*, *8*, 9, 10, *11*, 13, *14*, 15
1948	Jun	7	8, 9, 12, *13*, 14, 16, 17
1952	Feb	10	2, 3, 4, *5*, 6, 9, *10*, *11*, 7, 8
1954	Dec	10	1, 2, 3, 4, *6*, *8*, 10, *11*, 12, *14*
1960	Jul	11	1, *2*, 3, 4, 5, 6, *7*, 8, 9, 10, 12
1966	Feb	9	5, 6, 7, 8, 10, 11, 12, 14, 18
1970	Jul	7	1, *3*, 4, 5, 7, 12, 13
1972	Aug	7	1, *2*, *4*, *5*, 8, 9, 13
1974	Oct	8	3, 10, *12*, *13*, *14*, *15*, *17*, *18*
1976	Jan	16	*1*, *3*, *4*, *5*, 6, *7*, *8*, 9, 10, *11*, *12*, *13*, *14*, 15, 17, *18*
1977	Feb	12	1, *2*, 3, *4*, 5, *6*, *7*, *12*, 14, 15, 17, 18
1980	Jul	6	13, 14, 15, *16*, *17*, *18*
1982	Dec	8	*4*, 6, *9*, 10, *13*, 14, *15*, *16*
1985	Aug	9	1, 2, 3, 4, 5, 6, *7*, 9, 11
1996	Sep	8	*1*, 5, 6, 7, 8, 9, *14*, *16*
1997	Jul	8	*1*, 2, 3, *4*, 5, 6, 7, 10
2000	Mar	8	*1*, 2, 3, 4, *5*, 7, *8*, 9
2001	Jul	7	4, *5*, *8*, *9*, *10*, *11*, *14*
2004	Feb	7	4, 7, 8, 12, 14, 15, 18
2007	Sep	17	1, 2, *3*, *4*, 5, *6*, *7*, *8*, 9, 10, 11, *12*, 13, 14, 16, *17*, 18
2009	Mar	9	1, *2*, 3, 4, 8, 13, *14*, 15, 18
2010	May	18	*1*, *2*, *3*, 4, 5, *6*, *7*, *8*, *9*, *10*, *11*, *12*, 13, 14, 15, 16, *17*, 18

Maximum values in italics in 130 years

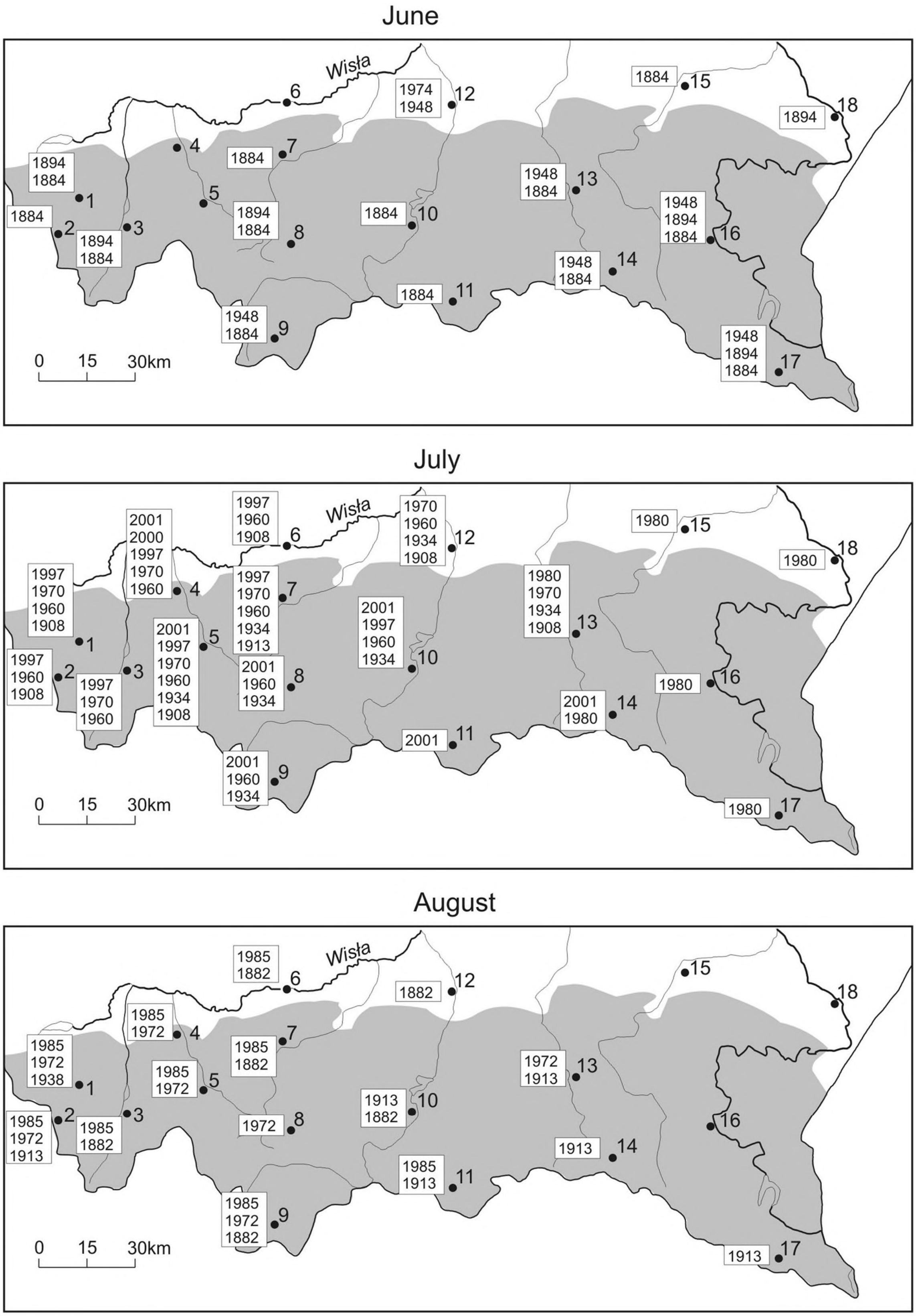

Fig. 5 AHP months in summer

The AHP season of spring 2010 is particularly noteworthy. It covers 12 stations in the western part of the area, including 8 where the precipitation totals were the highest of the study period (Table 8). The totals ranged from 351 mm (228 %) in

Table 10 Number of AHP seasons and AHP years recorded at the same time in station number ranges

Seasons	Number of stations												
	1	2	3	4	5	6	7	8	9	10	11	12	Σ
Spring	7	–	1	2	3	1	–	–	–	–	–	1	15
Summer	9	2	4	2	–	–	–	–	–	–	–	–	17
Autumn	4	6	1	3	3	–	–	–	–	–	2	–	19
Winter	8	3	1	1	–	–	–	–	–	–	–	–	13
Σ	*28*	*11*	*7*	*8*	*6*	*1*	–	–	–	–	*2*	*1*	*64*
Year	6	2	1	1	–	–	–	–	–	1	–	–	11

Maximum values in italics

Krakow to 662 mm in Wisła (247 %), while the greatest relative anomaly of 278 % was recorded in Wadowice (495 mm). In May of this anomalous season, all 12 stations also recorded AHP that triggered a flood in southern Poland (Maciejowski et al. 2011). This confirms a more general pattern where May was the crucial month contributing to springtime anomalies.

The two largest-scale autumn AHP seasons, in 1931 and 2007, occurred at 11 stations of the south-western and central part of the area.

The summer and winter seasonal anomalies were relatively small with a maximum of four to five stations in various parts of the study area. The summer AHP seasons were even smaller with two occurrences covering four stations each: an eastern part in 1893 and a western part in 1960. July precipitation contributed most to the summertime AHP seasons.

As has already been mentioned, six of the 11 years with AHP occurred at only a single station (Table 10). A notable exception in this sparse distribution was 2010 where the anomaly was recorded at ten stations scattered across the study area and with a maximum precipitation at each of them. The total precipitation in Krakow (1126 mm) represented the highest surplus over the average at 177 %. This anomaly owed its status not only to springtime precipitation, but also to that of the summer, which, in Krakow, was also an AHP season. The highest absolute precipitation total of this year was recorded in Krynica at 1344 mm (156 %).

Table 11 Frequency (%) of circulation types in southern Poland (Niedźwiedź 1981, 2014)

Circulation type		Jan	Feb	March	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Jan-Dec
1	Na	2.1	2.9	3.0	3.1	4.7	5.6	5.3	3.3	3.2	2.8	2.1	2.2	3.4
2	NEa	2.2	2.6	2.9	4.1	6.4	4.6	4.7	4.4	3.2	1.9	1.6	1.7	3.4
3	Ea	6.2	6.5	7.0	6.2	8.4	4.1	3.9	4.7	4.9	5.5	4.4	5.4	5.6
4	SEa	7.2	7.8	7.2	4.7	4.2	1.9	1.2	2.8	5.2	7.3	6.5	6.5	5.2
5	Sa	3.1	3.6	3.9	2.9	2.4	1.6	1.3	2.4	4.1	5.6	5.5	3.8	3.3
6	SWa	6.0	3.8	3.3	2.7	2.0	1.9	1.7	3.2	5.2	6.9	6.9	6.1	4.2
7	Wa	*15.3*	*11.9*	7.9	4.9	4.2	7.4	10.2	12.0	11.0	*11.7*	11.9	13.6	10.2
8	NWa	5.3	5.4	5.2	3.5	3.8	6.9	7.0	6.0	6.6	4.7	4.6	4.6	5.3
9	Ca	2.8	2.1	1.5	1.2	1.5	1.9	1.8	2.7	3.5	3.2	2.1	2.3	2.2
10	Ka	10.0	8.7	9.3	11.8	12.4	*14.5*	*16.2*	*16.3*	*14.4*	11.4	9.9	9.5	12.0
11	Nc	1.6	2.5	2.5	3.8	3.4	4.4	4.1	2.9	2.2	1.4	1.3	1.5	2.6
12	NEc	1.1	1.6	1.6	3.2	3.0	3.6	2.5	2.3	1.5	1.2	1.1	1.1	2.0
13	Ec	1.8	2.3	3.1	3.9	4.1	3.0	1.2	1.0	1.6	1.9	1.8	1.8	2.3
14	SEc	2.2	3.2	3.8	4.8	3.5	2.2	1.1	1.4	1.7	1.9	3.3	2.6	2.6
15	Sc	2.7	3.8	3.6	4.4	3.6	1.4	1.3	1.5	2.4	3.5	5.1	3.4	3.1
16	SWc	5.7	6.6	6.7	5.5	4.4	2.4	2.6	2.8	3.9	6.5	7.0	6.9	5.1
17	Wc	12.7	11.4	*10.6*	8.7	6.0	8.1	11.6	10.5	10.0	10.2	*12.1*	*14.0*	10.5
18	NWc	5.1	4.9	5.5	5.0	4.8	7.2	7.9	5.6	4.4	3.5	4.1	4.6	5.2
19	Cc	0.6	0.9	0.8	1.7	1.5	1.6	0.9	1.0	0.7	0.8	0.9	0.6	1.0
20	Bc	4.5	5.7	8.4	*11.9*	*13.9*	14.1	12.3	12.0	8.4	6.6	6.4	6.0	9.2
21	X	1.6	1.8	2.0	2.0	1.8	1.5	1.0	1.5	1.8	1.7	1.5	1.6	1.7
1–21	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1–10	a	60.2	55.3	51.3	45.0	49.9	50.5	53.4	57.7	61.3	60.7	55.5	55.8	54.7
11–20	c	38.1	42.9	46.6	52.9	48.3	48.0	45.6	40.8	37.0	37.6	43.0	42.6	43.6

Maximum values in italics

a anticyclone types, *c* cyclonic types

There are only two other AHP years of note. That of 1966 was recorded at four stations in different parts of the area, including Bielsko-Biała with a highest total of 1508 mm (152 %) and Krakow with the highest surplus of 156 % (1000 mm). In 1939, three stations recorded a year with AHP (AHP year) ‘with totals of around 1200 mm.

7 Atmospheric circulation vs. AHP

Certain features of atmospheric circulation are regarded among key causes of precipitation. Many other Polish researchers have identified and documented the effect of circulation on high daily precipitation totals in the Carpathian Mountains and their foreland. In general, their findings link this precipitation to cyclonic circulation. In his study, Niedźwiedź et al. (2009) go so far as to conclude that more than 60 % of the variability of precipitation totals in this area can be explained by variability of the cyclonicity index. The authors also demonstrated that macro-scale atmospheric circulation (NAO) had only minor influence on precipitation in Central Europe that amounted to 4 % of the variance of the annual precipitation and up to ca. 40 % of the variance of winter precipitation.

To determine what circulation conditions lead to the formation of anomalously heavy monthly precipitation, the authors investigated the frequency of circulation types in southern Poland using a calendar proposed by Niedźwiedź (1981, 2014). Discussions of this calendar, which includes 21 circulation types, can be found in numerous studies (e.g. Twardosz 2009; Niedźwiedź et al. 2009).

The study looked at the frequency of circulation types throughout the 130-year study period (Table 11) and in the 212 (Table 2) AHP months (Table 12) and at selected months with AHP recorded at all stations, at stations in the western part and at stations in the eastern part of the area (Table 13). This procedure produced a somewhat simplified picture of the types of circulation conducive to the formation of heavy precipitation. To obtain a full picture, the numbers of days with various ranges of precipitation totals at each station would have to be taken into account to differentiate between cyclonic and convective precipitation types.

Table 12 Frequency (%) of circulation types in southern Poland during the 212 AHP months (number of calendar months with AHP months as in Table 2)

Circulation type		Jan	Feb	March	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1	Na	1.6	2.0	5.3	2.5	4.9	6.5	6.1	4.9	3.0	2.2	1.1	2.8
2	NEa	2.0	2.5	1.4	3.7	5.8	5.1	4.5	5.7	5.0	2.2	0.9	1.6
3	Ea	5.8	4.5	4.4	6.7	5.6	1.7	2.0	5.1	7.0	6.7	2.0	3.0
4	SEa	7.3	5.1	4.1	2.3	3.4	1.2	0.4	2.7	5.7	5.0	4.0	2.5
5	Sa	3.2	1.6	2.1	1.1	1.5	1.4	0.9	1.3	2.6	2.0	3.6	3.2
6	SWa	3.2	0.8	3.9	1.9	1.3	1.3	1.1	2.7	4.3	5.2	3.6	4.4
7	Wa	12.7	11.7	9.9	4.7	4.3	4.8	7.7	10.1	8.0	12.2	10.2	16.1
8	NWa	6.9	4.1	7.1	3.0	4.1	5.5	5.7	4.7	6.9	2.7	4.9	5.3
9	Ca	1.2	0.8	1.2	1.1	0.4	1.9	1.3	0.9	0.7	2.2	0.9	2.5
10	Ka	7.3	6.1	6.5	10.2	12.0	12.3	13.6	12.5	9.6	7.2	8.9	6.5
11	Nc	2.8	4.9	4.6	6.5	7.5	8.0	10.4	5.9	4.4	2.5	2.4	1.6
12	NEc	1.2	3.1	2.1	4.6	4.9	5.7	3.4	4.6	2.6	2.7	1.6	2.1
13	Ec	1.8	2.3	2.3	3.3	4.5	3.9	0.9	0.9	2.2	3.7	2.9	1.4
14	SEc	1.2	4.1	3.2	3.2	5.8	1.6	1.6	1.9	3.1	1.5	3.8	2.3
15	Sc	1.6	4.3	4.4	4.6	3.2	1.0	1.1	1.3	2.4	3.5	5.8	6.2
16	SWc	6.3	8.4	5.3	6.3	3.4	2.8	3.0	2.1	3.7	5.5	8.0	4.1
17	Wc	*16.9*	*14.3*	*12.2*	9.6	3.9	8.8	9.5	10.6	10.0	*15.1*	*18.9*	*16.6*
18	NWc	9.3	8.8	8.1	5.1	5.8	8.3	9.1	6.8	5.9	4.7	5.8	8.1
19	Cc	0.4	1.4	0.9	2.5	1.9	2.6	0.7	1.3	0.7	2.2	2.0	1.2
20	Bc	5.0	7.4	9.4	*14.9*	*14.0*	*14.9*	*15.1*	*12.7*	*10.7*	9.4	7.1	6.7
21	X	2.2	2.0	1.6	2.5	1.5	0.7	2.0	1.1	1.3	1.5	1.8	1.8
1–21	Total	100	100	100	100	100	100	100	100	100	100	100	100
01–10	a	51.2	39.1	45.9	37.0	43.4	41.7	43.2	50.9	52.8	47.6	40.0	47.9
11–20	c	46.6	59.0	52.5	60.5	55.1	57.5	54.8	48.0	45.9	50.9	58.2	50.2

Maximum values in italics

Table 13 Frequency (%) circulation types in southern Poland in selected AHP months

Circulation type		Jan 1976	Feb 1946	May 1940	May 2010	Jul 1960	Jul 1980	Sep 2007
1	Na	3.2	3.6	–	–	–	–	–
2	NEa	3.2	–	–	3.2	–	–	–
3	Ea	–	–	16.1	–	–	–	–
4	SEa	3.2	–	6.5	–	–	–	–
5	Sa	–	–	–	–	3.2	–	3.3
6	SWa	–	–	3.2	–	–	–	10.0
7	Wa	3.2	17.9	3.2	–	16.1	12.9	10.0
8	NWa	–	7.1	3.2	3.2	6.5	–	20.0
9	Ca	–	–	–	–	3.2	–	–
10	Ka	12.9	3.6	6.5	9.7	12.9	6.5	10.0
11	Nc	3.2	7.1	6.5	16.1	16.1	9.7	3.3
12	NEc	3.2	–	6.5	12.9	3.2	6.5	3.3
13	Ec	3.2	–	19.4	3.2	–	6.5	–
14	SEc	–	–	9.7	3.2	–	–	3.3
15	Sc	–	–	–	9.7	3.2	3.2	3.3
16	SWc	–	7.1	–	–	–	9.7	3.3
17	Wc	29.0	32.1	–	–	6.5	16.1	6.7
18	NWc	19.4	14.3	6.5	12.9	3.2	3.2	10.0
19	Cc	–	–	–	–	–	–	–
20	Bc	9.7	7.1	12.9	25.8	12.9	22.6	13.3
21	X	6.5	–	–	–	12.9	3.2	–
1–21	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
01–10	a	25.8	32.1	38.7	16.1	41.9	19.4	53.3
11–20	c	67.7	67.9	61.3	83.9	45.2	77.4	46.7

A certain predominance towards anticyclonic circulation (55 %) is a typical feature of the atmospheric circulation variability over southern Poland (Table 11). Cyclonic circulation prevailed only in April (53 %). As was expected, cyclonic circulation was found to favour the occurrence of AHP months. It is important to point out here that it was not a case of an absolute prevalence of cyclonic circulation types, but their above-average frequency during AHP months. The greatest frequency of cyclonic types during AHP months was found in April at 60 %, which is 8 % more than the average. The greatest difference than the two frequencies was found in February at 16 % (with 43 %, on average, and 59 % in an AHP months) and in November at 15 % (43 and 58 %).

Generally, the type of circulation, i.e. cyclonic vs. anticyclonic, has a stronger impact on the formation of an AHP than the direction of air advection. In all AHP months, there occurred one of the most frequent circulation types, i.e. western cyclonic circulation (Wc) or cyclonic trough (Bc). Between October and March, western cyclonic type prevails ranging from 12 % in March (compared to the average of 10.6 %) to 19 % in November (12.1 %). Other cyclonic types of the western sector, SWc and NWc (combined 9–17 %), and the Wa type (10–16 %) also played a considerable role. In winter, especially in January, the mid-latitude frontal disturbances have a tendency to converge over Poland producing higher precipitation totals in western advection than with other sectors (Twardosz 2009). For the rest of the year, the cyclonic trough Bc is more frequent, at 11–15 %, on average, followed in frequency by high-pressure wedge Ka, at 10–14 %. Cyclonic trough was found to be most conducive to AHP months in the eastern part of the area; e.g. in July 1980, its frequency was 23 % or twice as high as the average of this month (Table 13). In summer AHP months, northern sector circulation was also more frequent, especially in the western part of the area. For example, in July 1960, the frequency of just one of the types in this sector, Nc, was four times higher than the average (Table 13). These circulation types were conducive to heavy and lasting precipitation, primarily in cold or stationary front zones (Twardosz 2009). Similar patterns of circulation influence causing heavy precipitation were identified in other areas of the country (Kossowska-Cezak 1997). The same circulation types accompanied nearly all days with precipitation in Krakow during AHP of May of 2010 (Woźniak 2012). High monthly precipitation totals in southern Poland can also coincide with anticyclonic circulation types, especially the anticyclonic wedge Ka (Twardosz 2009). In summer, local downpours can form in uniform air masses as a result of strong thermal convection.

In May 2010, anomalously high precipitation totals in the entire Polish Carpathian Mountains were accompanied primarily by cyclonic trough (Bc) and northern circulation, both twice as frequent as the average (Table 13). The AHP of May 1940 also covered the entire area, but the totals were lower. Eastern circulation, mainly cyclonic, dominated for more than one third of that month (Table 13).

8 Conclusion

The study identified anomalously heavy precipitation (AHP) at 18 stations in the Polish Carpathian Mountains and their foreland over a 130-year period spanning 1881–2010. A rather stringent statistical criterion was used as a cut-off at the upper quartile value plus 1.5× of the interquartile gap.

It was demonstrated that while AHP occurred in all months, in seasons and in entire years, they were also infrequent. There were between one monthly AHP (months with anomalously heavy precipitation, AHP months) per 5 years in June to one AHP month per 10 years in October and between one AHP season (season with AHP) per 7 years in autumn to one AHP season in 10 years in winter.

Most AHP was spatially limited to one or two stations, typically neighbouring ones, thus clearly suggesting that local conditions, as well as circulation-related factors, influenced their occurrence.

AHP recorded in May had the largest area coverage with an average of five stations, while those recorded in November were the smallest at two stations on average.

Two AHP months were recorded at all 18 stations: in May 1940 and May 2010. Both triggered catastrophic floods. The event of 2010 involved both the highest absolute precipitation totals of more than 500 mm in the western part of the area and the highest relative values, i.e. surplus over the long-term average. In 1940, the highest relative anomaly was recorded in Bielsko-Biała (487 %). Other large-scale AHP months (15–17 stations) were recorded in September 2007, January 1976, February 1946 and May 1939.

Cyclonic circulation, as expected, prevailed in months with AHP. Between October and March, western sector circulation types prevailed, especially the western cyclonic type (Wc), while, for the rest of the year, it was the cyclonic trough (Bc) followed by an anticyclonic wedge (Ka). These opposite circulation types point to the alternative origins of AHP: either on active atmospheric fronts or on convective types.

In terms of the hydrological and geomorphological effects of AHP, the least dangerous are the AHPs recorded in winter which may have similar surplus values to those occurring in other seasons but feature the lowest totals of all, are the least frequent and cover the smallest areas at a time (one to two stations). This effect is explained by the annual precipitation cycle, which reaches its lowest point in winter. Summer AHP events also covered small areas (no more than four stations), due to the local nature of rainfall of convectional origin, but are more frequent than in winter and feature the highest rainfall totals (up to 600–800 mm). AHP in spring and autumn covers the largest areas (11–12 stations).

Generally, AHP was demonstrated to be a rare and spatially limited phenomenon. Indeed, during the 130 years of the study period, there were no AHP seasons that would cover all of the stations in a single season. They were overwhelmingly up to one third of the stations (6/18).

The results of the study have a potential practical application due to the information on the frequency, scale and spatial coverage of AHP in various seasons in southern Poland, a region characterised by average precipitation higher than anywhere else in the country (except the Sudety Mountains) and which may lead to dangerous hydrological or geomorphological events, such as floods and landslides.

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